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Applying image processing method to treat digital signals*

WANG Peng (王鹏),[1] ZHANG Ruan-Yu (张软玉),[2,†]
YUAN Xue-Dong (袁学东),[2] XU Zu-Run (许祖润),[2] and AN Zhu (安竹)[1]

[1]*Institute of Nuclear Science and Technology of Sichuan University, Key Laboratory of Radiation Physics and Technology, Ministry of Education, Chengdu 610064, China*
[2]*The College of Physics Science and Technology of Sichuan University, Chengdu 610064, China*
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In this paper, we present a novel method for digital nuclear signal processing based on image processing and recognition, which can improve signal-to-noise ratio of digital nuclear signal effectively without changing the signal shape. The digital nuclear signal with a "time-amplitude" series is converted into a grayscale image with adjustable pixel size. Template of the converted image is extracted by means of modern image processing methods, such as spatial digital low-pass filtering, image binary and the skeleton extracting of images. The needed parameters are extracted from the template image. The method of template extracting presented in this paper can be used flexibly to extract template of nuclear signals, whether the whole or even part of that, and got multi templates corresponding to the whole or partial characters of the signals. The results of image processing, along with γ-ray energy spectrum of ^{241}Am acquired by this method, show that the new method provides a way to develop future digital nuclear instruments of high efficiency and flexibility, high density and multi parameters.

Keywords: Image of digital nuclear signal, Skeleton extracting, Waveform information extracting

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I. INTRODUCTION

Digitalized nuclear instrument has been widely used in high-energy physics, nuclear physics and applied nuclear physics. Time domain analysis is a conventional method in digital nuclear signal processing, such as filtering or shaping, for those signals described as amplitude-sampled series with equal time interval. For example, nuclear signals are normally shaped to trapezoid or triangle signals in energy spectrum measurement [1, 2] and shaped to bipolar signals for accurate timing in time measurement [3, 4]. Different configurations of hardware and software should be made according to different measurement requirements. Complexity of the system appearing in real-time and multi-task measurements costs huge resources and degrades real-time performance of the system.

To solve these problems, we propose a method for digital nuclear signal processing to acquire nuclear information. In applying the method of image processing, the following points are taken into account: (1) the shape of output signal from a nuclear detector is determined after parameters of the system are set; (2) different information of nuclear radiation is carried by the whole signal like the rising edge, flat top and shape of the nuclear pulse; (3) valuable achievements, theoretical or experimental, of digital image processing can be adopted [5, 6]. In this paper, we focus on converting a digitized nuclear signal waveform into a digital image, template-extracting from the converted image, and reconstructing the waveform from the templates. Compared with the original digital signal, the overshooting of reconstructed signal is effectively eliminated and the signal-noise ratio is apparently improved, without changing its shape. γ-ray spectrum of ^{241}Am was collected to validate our algorithm of the image processing method. The results show that resolution of the energy spectrum achieved by our algorithm is better than that from the MCA of ORTEC Inc.

II. IMAGE CONVERSION OF DIGITAL NUCLEAR SIGNAL

A. Principle and method

Assuming that an output signal of nuclear detector of $\nu(t)$, with time duration of T and amplitude of A, is discretized into digital signal $\nu(n)$ by ADC of N-bit precision and $1/T_s$ sampling frequency. In another word, $\nu(n)$ consists of a series of amplitude values of equal time interval $1/T_s$. Next, we try to convert it into an image of $w \times h$ pixels with gray scales of 2^M (M is a positive integer). Here, we may deduce that the maximum horizontal and vertical resolutions of the image are $W = [T/T_s]$ and $H = [A/V_{OM} \cdot 2^M]$, respectively. V_{OM} is the maximum output value of ADC, N is the bit number of ADC, and when $A = V_{OM}$, we have $H = 2^N$. The symbol "[]" denotes that W and H can just be integers. The conversion procedure is described as follows. Firstly, assuming the width and height of each pixel being Δw and Δh respectively, the waveform $\nu(n)$ is divided into $w \times h$ grids of rectangle $\Delta w \times \Delta h$. So we have $w = [W/\Delta w]$ and $h = [H/\Delta h]$, and each grid denotes a pixel of the converted image, as shown by thick-border rectangle in Fig. 1(a). Normally, $\Delta w \geq 1$ and $\Delta h \geq 1$, i.e., several sampling points of different sampling time may be "drawn" into the same grid if their amplitude and time resolutions belong to the same pixel (x, y). Secondly, count the number of each pixel, as shown in Fig. 1(b),

* Supported by National Natural Science Foundation of China (No. 11075111)
† Corresponding author, softyv@vip.sina.com

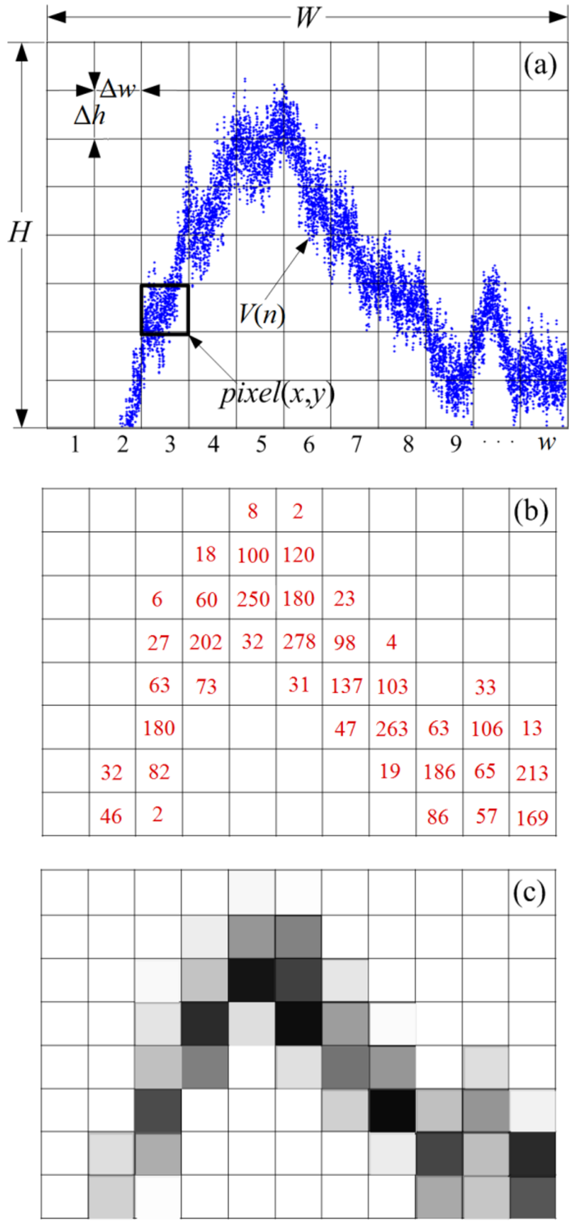

Fig. 1. (Color online) Illustration of image conversion of a digital signal: (a) divide the waveform into grids of w rows and h columns, (b) calculate the grayscale value of each grid, (c) converted grayscale image.

and calculate the grayscale (ψ) of each pixel according to its count number by Eq. (1):

$$\psi = \left[\frac{Z(x,y)}{Z_{\mathrm{MAX}}} \times 2^{M} \right], \tag{1}$$

where $Z(x,y)$ is count number of the pixel (x,y) and Z_{MAX} is maximum count of all pixels.

Finally, by drawing each pixel with corresponding grayscale value, the waveform of "amplitude-sampled" series with equal time interval is converted into "x–y" series two-dimensional grayscale image (Fig. 1(c)).

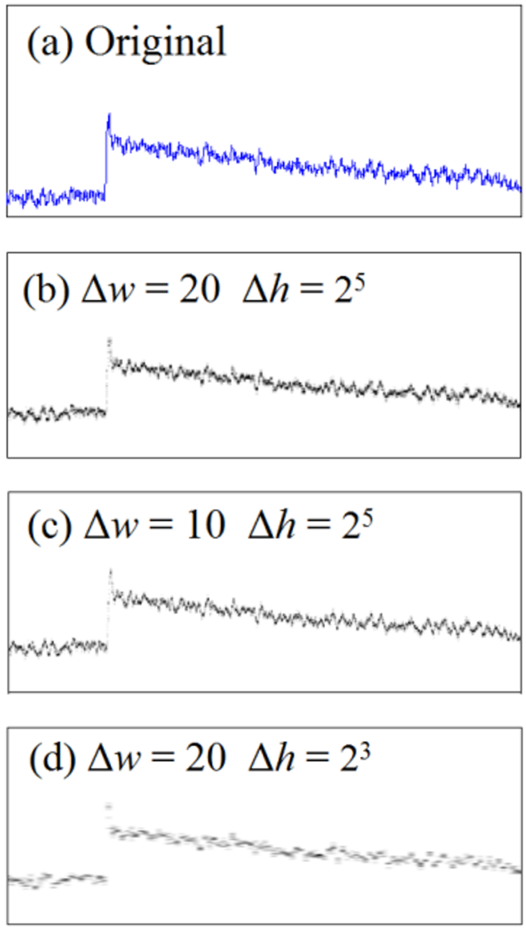

Fig. 2. (Color online) Comparison of original waveform (a) and image conversion results with pixel sizes of 20×2^5 (b), 10×2^5(c) and 20×2^3(d).

B. Parameter confirmation of image conversion

The data amount of the converted image is determined by the size of Δw and Δh. The possible maximum data amount of image pixels of the waveform is $W \times H$, and actually the mount of pixels of an converted image depends on the size of Δw and Δh. In Fig. 2, a digitized nuclear waveform is converted into grayscale image with different values of Δw and Δh. It can be seen that the largest $\Delta w \times \Delta h$, i.e. the least data amount, is of the most distinct image profile. This is fit for image conversion of the waveform sampled from low-frequency ADC. On the contrary, the smallest $\Delta w \times \Delta h$, i.e. the largest data amount, presents the most detailed waveform. This is suitable for image conversion of the waveform sampled from high-frequency ADC.

III. THE IMAGE ENHANCEMENT AND TEMPLATE EXTRACTING

The converted image includes also noise and interference superposed on the nuclear signals. They can be reduced by

the image processing procedure of image enhancement of digital nuclear signals (IES). The nature of IES is to weaken scrambled noise imposed on the waveform by the spatial smooth filtering of the image, which improves of the image profile by analysis and recognition of the waveform as follows.

A. The spatial digital low-pass filtering

Assuming an image size $f(x+s, y+t)$ is $w \times h$, the spatial average filtering of the grayscale image of waveform is completed through 2-D convolution with a filter mask ω of $m \times n$ size, we have the filtering result using Eq. (2) [7]:

$$g(x,y) = \sum_{s=-a}^{a} \sum_{t=-b}^{b} \omega(s,t) f(x+s, y+t), \qquad a = (m-1)/2, \quad b = (n-1)/2, \tag{2}$$

where $s = 1, 2, \ldots, m$ and $t = 1, 2, \ldots, n$ are independent variables of mask function; and $f(x+s, y+t)$ denotes grayscale value of the pixel $(x+s, y+t)$ in the image, $x = 0, 1, 2, \cdots, w-1$, $y = 0, 1, 2, \cdots, h-1$. The filtering result is shown in Fig. 3. Fig. 3(a) is the image of nuclear signal before filtering and Fig. 3(b)– 3(d) are images after filtering with Eq. (2) using different filter masks. The filtering effect is related with the filter mask size. Generally, a smaller filter mask is of worse performance of spatial smooth filtering, but a lager filter mask causes bigger statistical error in acquiring signal amplitude. So, in choosing the filter mask size, the actual property of noise imposed on the signal shall be taken into account. Considering the mean square value of the noise, and statistical error of the acquired signal amplitude, the filter mask of 15×15 is an optimal choice under our experimental noise circumstance.

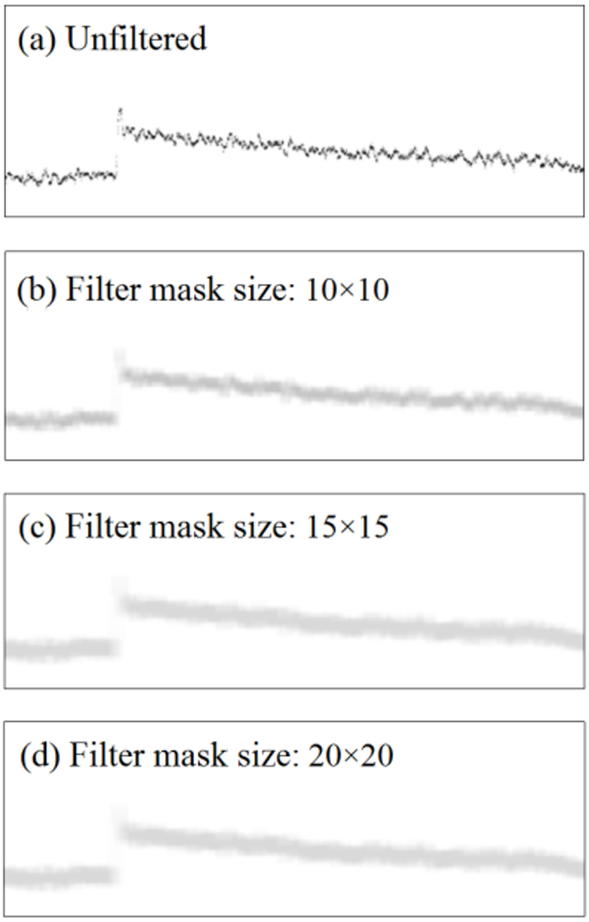

Fig. 3. Comparison of spatial average filtering without (a) and with filter mask in sizes of 10×10 (b), 15×15 (c) and 20×20 (d).

B. Image skeletonization and template extracting

A key factor of constructing an optimal signal processing system in digital nuclear measurement and analysis is to recognize parameters of the detector system accurately. A method called "template extracting" is introduced to complete the task based on image skeletonization, developed from the theories of mathematical morphology.

The skeleton $S(f)$ of specific image $f(x,y)$ can be expressed as the union of a series of erosion and opening operations of morphological image processing, which can be described as follows [8]:

$$S(f) = \bigcup_{k=0}^{K} S_k(f), \tag{3}$$

$$S_k(f) = (f \Theta kB) - (f \Theta kB) \circ B, \tag{4}$$

where, B is the structuring element, "$\circ$" denotes the opening operation, and $(f \Theta kB)$ denotes k times continuous erosions of f.

$$(f \Theta kB) = \{(f \Theta \underbrace{B) \Theta B \cdots \Theta B}_{k}\}, \tag{5}$$

where, k is the time of the last iteration of erosions before $(f \Theta kB)$ becomes empty set, described as Eq. (6):

$$K = \max\{k | (f \Theta kB) \neq \varnothing\}. \tag{6}$$

For practical application, K can be set to a fixed value as a tradeoff between calculation speed and the effect of skeleton extracting. According to theories of digital image processing, the waveform image after spatial low-pass filtering is converted into binary image, where the gray scale value of any pixel above 1 is forced "on" and below 1 is forced "off". The template of image is then extracted by skeletonizing of the binary image with corresponding structuring element [9, 10].

In this work, we use the function "bwmorph(BW, 'skel', K)" of MATLAB to perform skeleton extracting of the binary image. The function "bwmorph" can perform all sorts of morphological operations on binary images depending on its parameters. There are three parameters of "bwmorph": "BW" denotes the image to be processed, "skel" implies that

the operation is used to extract skeleton of the image by removing pixels on the boundaries of objects but not allowing objects to break apart, and "K" means the operation is applied for K times. Here we used a structuring element of 3×3 size (Eq. (7)), being used to implement fast erosion algorithm based on look-up table [11].

$$B = \begin{vmatrix} 256 & 32 & 4 \\ 128 & 16 & 2 \\ 64 & 8 & 1 \end{vmatrix}. \tag{7}$$

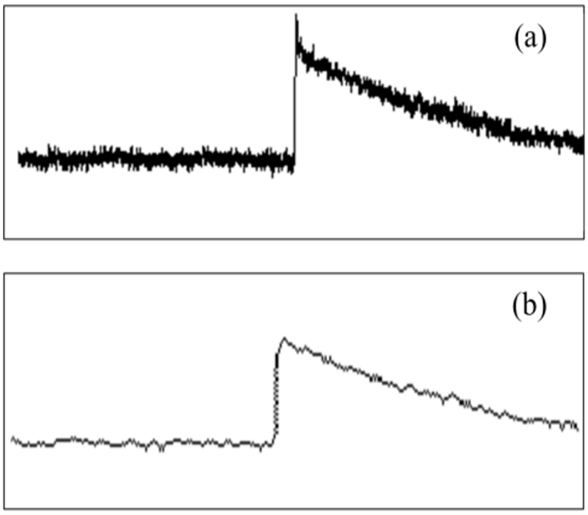

Fig. 4. The waveform of ^{241}Am γ-ray at 100 MSPS sampling rate (a), and the skeleton of waveform (b).

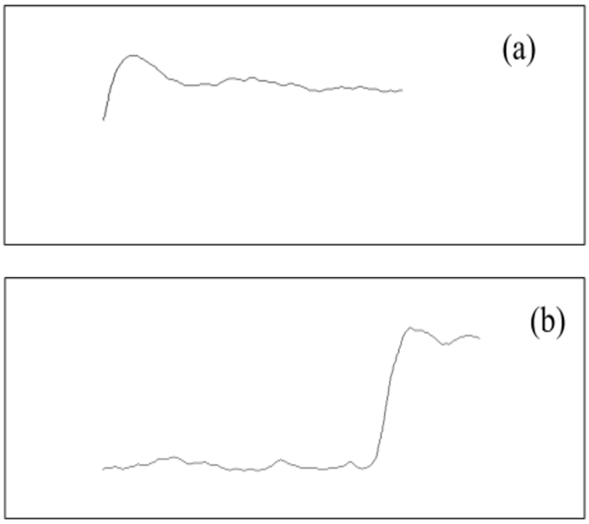

Fig. 5. The templates of different part of one signal. (a) The template of the top of signal; (b) The template of the rising edge of signal.

Figure 4 shows the template of nuclear signal waveform after skeletonizing. Fig. 4(a), is the time-amplitude waveform of ^{241}Am γ-ray detected by CZT detector, sampled by Lecroy WaveRunner 104Xi-A oscilliscope at the sampling rate of

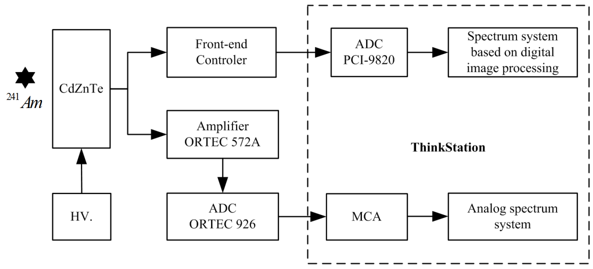

Fig. 6. The block diagram of the experimental apparatus.

100 MSPS, and Fig. 4(b) demostrates the skeleton of waveform through image conversion, image enhancement and image skeletonizing. Moreover, we could get multi-style templates from one system by extracting skeletons of different parts of the same waveform through handling different parts of the waveform image. Fig. 5 shows the extracted templates of the part of rising edge and the part of flat top according to Fig. 4(b). The image skeletonizing of digital nuclear signals from different radiation sources, detectors and sampling rates can all be completed by this method, with some adjustment of values of corresponding parameters. The method we presented lays the fundation of high-precision parameter recognition of the waveform.

It can be seen from Fig. 4 and that compared with the original image, the noises imposed on the skeleton are reduced obviously, with the skeleton shape being almost unchanged for both the rising and falling edges. The skeleton has the features of the whole or the key parts of nuclear signal waveform acquired from the detection system under certain working conditions, which can be used as template of nuclear signal waveforms.

IV. RESULTS AND DISCUSSION

A. Acquisition of amplitude of template image

We try to describe the basic features of template image in the form of parameters after setting up the template image. The amplitude of signal denoted by template image is defined as Eqs. (8) and (9),

$$\nu_N = (N - N_0)\Delta\nu, \tag{8}$$

$$\Delta\nu = \nu_{\text{range}}/H, \tag{9}$$

where ν_N is the amplitude value represented by row N of template image, N_0 is row number of template image which denotes the amplitude of zero, $\Delta\nu$ is the amplitude value represented by a row, ν_{range} is the input range of the digitizer, and H is the maximum vertical resolution of the image defined in Sec. II (A).

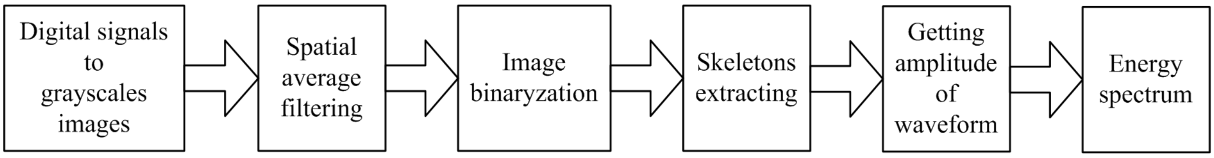

Fig. 7. The flowchart of acquisition of energy spectrum by algorithm based on digital image processing.

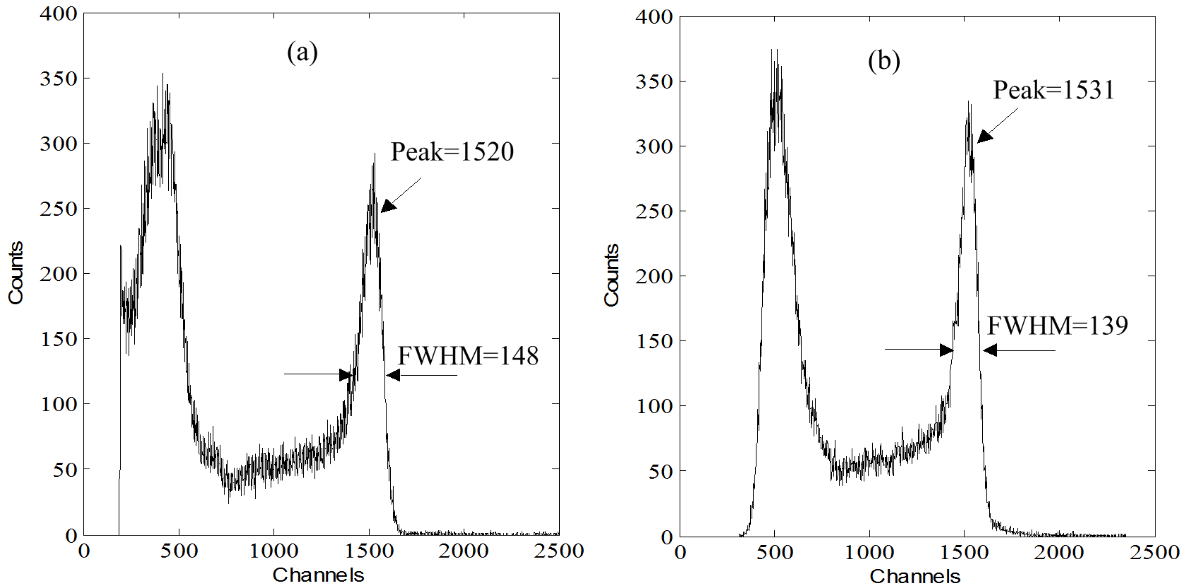

Fig. 8. Comparison of spectra from (a) a conventional MCA and (b) the image processing algorithm.

B. Acquisition of spectrum

In order to demonstrate effectiveness of the proposed method, a system is established to acquire the nuclear energy spectra with this method and the conventional MCA, and to compare their results.

Figure 6 is a block diagram of the system. The ^{241}Am γ-ray signals from the CZT detector are fed simultaneously into the digital spectrometer and the MCA composed mainly of the ORTEC-527 amplifier and ORTEC-926 ADC. The digital spectrometer constitutes of FA-001 front-end controller and PCI-9820 digitizer (AD-LINK). Sampling rate of the ADC is 66 MSPS, with conversion accuracy of 14-bit and input range of ± 1 V. The digital nuclear signals acquired by waveform digitized system are transferred to the workstation for data process and result analysis [12]. The data are processed by an algorithm based on image processing discussed above. Fig. 7 shows the flow steps to collect the energy spectrum from digitizer by the algorithms. Parameters for the steps are given in Table 1.

Figure 8 compares the two spectra acquired by the conventional MCA (Fig. 8(a)) and the algorithm based on image processing (Fig. 8(b)). From Fig. 8, one sees that our image processing algorithm has the good ability to acquire nuclear information, such as acquisition of amplitude information of the waveform. The resolutions of peak at 59.5 keV are 9.7% and 9.1% in Figs. 8(a) an 8(b), respectively, an obvious improvement of the energy resolution by our digital image processing method. Successive efforts are being made for further improvement of the new method.

TABLE 1. Parameters used in the algorithm

Steps	Parameters
Convert to grayscale image	$W = 5000$, H=2^8, Δw=10, $\Delta h = 2^5$
Spatial average filtering	filter mask:15 $\times$ 15 pixels
Skeleton extracting	structuring: 3 $\times$ 3 pixels, $K = 10$

V. CONCLUSION

According to the experimental results above, the following conclusions can be made: (1) it is feasible to adopt digital image processing methods into the digital nuclear signal processing for nuclear information acquiring; (2) digital nuclear signal can be successfully converted into grayscale image with adjustable gray scale and size through our method; (3) the skeleton of nuclear signal image can be extracted through the combination method of the spatial linear filtering and mathematical morphology, and has the potential advantages

for further use in setting-up template library for nuclear signals recognition; and (4) the method we presented will make many potential applications simple and effective, such as signal accumulation discrimination, weak signal finding and the compression and transferring of digital nuclear signal data, which will be studied later.

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